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Optical Disc System for Digital Video Recording

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We have developed a new error correction method (Picket: a combination of a long distance code (LDC) and a burst indicator subcode (BIS)), a new channel modulation scheme (17PP, or (1, 7) RLL parity preserve (PP)-prohibit repeated minimum transition runlength (RMTR) in full), and a new address format (zoned constant angular velocity (ZCAV) with headers and wobble, and practically constant linear density) for a digital video recording system (DVR) using a phase change disc with 9.2 GB capacity with the use of a red (λ = 650 nm) laser and an objective lens with a numerical aperture (*NA*) of 0.85 in combination with a thin cover layer. Despite its high density, this new format is highly reliable and efficient. When extended for use with blue-violet ($\lambda \approx$ 405 nm) diode lasers, the format is well suited to be the basis of a third-generation optical recording system with over 22 GB capacity on a single layer of a 12-cm-diameter disc.

KEYWORDS: optical recording system, DVR, error detection and correction code, picket, channel modulation, parity-preserve, RMTR, address format, wobble, header, video recording system, consumer application, home video, high *NA*, thin cover, blue laser diode

1. Introduction

Two major technological breakthroughs have been achieved in the last two years, which together allow a large increase in optical disc capacity. First, high numerical aperture (*NA*) objective lenses have become feasible by using two-element lenses: *NA* = 0.85 lenses can be applied with sufficient system margin when readout is performed through a thin transparent cover layer of 0.1 mm thickness,[1–3] instead of reading out through a 0.6-mm-thick substrate as is done for the digital versatile disc (DVD). Second, tremendous progress in the field of blue-violet diode lasers has been made over the last two years:[4] diode laser samples with a wavelength around λ = 400–410 nm and sufficient lifetime and output power have recently been realized, and will soon be commercially available. These combined breakthroughs allow a reduction of the focussed spot size (which is proportional to $(\lambda/NA)^{2)}$), by a factor of about 5 when compared with DVD, thus allowing a capacity of 22 GB on one layer of a 12-cm-diameter single-sided disc. This opens the way for (real-time) recording of bit-hungry high-quality video streams.

In this paper, we present the system design criteria (§2), the disc structure (§3), and a full format description and verification for a rewritable optical disc for the digital video recording system (DVR) with recording and playback through a thin cover layer with a red laser and an *NA* of 0.85, yielding a disc capacity of 9.2 GB. More specifically, we present a new error correction method (§4), a new channel modulation code (§5), and a new address format (§6), together with their experimental integration and evaluation (§7). This full format has an increased efficiency compared to conventional optical disc formats and is highly reliable, despite its high density.

More details on the various enabling technologies for the DVR optical disc system are described in a number of associated papers, presented together with our paper at the Joint International Symposium on Optical Memory and Optical Data Storage 1999.[5–9] Specifically, these papers discuss the cover layer technology,[5] various options for phase-change media with 9.2 GB disc capacity with the use of a red laser[6,7] and with 22 GB capacity with a blue-violet diode laser,[7,8] and the feasibility of dual-layer recording[9] in the high-*NA* thin cover layer approach.

The red format development described in detail in this paper allows extension to capacities of 22 GB and more when blue-violet diode lasers (λ around 405 nm) are implemented in our system.

2. Requirements for Digital Video Recording

The format presented in this paper is intended for use in a optical disc based digital video recorder. Although a detailed discussion of the digital video recording application is beyond the scope of this paper we will give a few general comments to emphasize the importance of a suitable disc format for this application.

Key issues for recording of high-definition (HD) video and to enable advanced features are a high (user) data rate and a high (user) capacity. In the HD application, a high data rate and a high capacity are imperative to be able to deal with the HD-rate and realize sufficient playing time. For special features such as dual stream operation, *e.g.* simultaneous recording and play-back from one disc using a single optical pickup, the user data rate of both streams must be sustained without interruption. Accesses have to be performed because the data may be scattered over the disc and, as a consequence, the net user rate will be lowered as a result of read and write actions with seeks and accesses in between. Various parameters such as seek time, fragmentation, read data rate and write data rate have to be taken into account to estimate the resulting user rate. However, it is clear that the time lost in seek operations has to be compensated by a higher disc rate. Therefore, a high disc rate and a disc format which allows fast access are very important.

We made some rough estimates of the required performance for a few application areas:

1) Recording of 4 h of DVD-quality video requires a 9 GB disc capacity.

2) Dual-stream operation of two DVD-quality video streams requires data rates of 30–35 Mbps and a disc capacity

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Table I. Video application areas, user requirements and system options. Note DVD allows variable bit rate (VBR) video, thus two source data rates are given: the maximum and (typical) average. The other examples (BS4B and DV) are constant bit rate (CBR) video streams.

	Source video rate data	Disc capacity	Required data rate to/from disc	System
4 h of DVD video	10 Mbps max.; 4.5 Mbps average	9 GB	10–15 Mbps	650 nm, $NA = 0.85$
2 streams of DVD-quality video (2 h each)	2–10 Mbps	9 GB	33 Mbps	650 nm, $NA = 0.85$
2 h of HD video	24 Mbps (BS4B)	22 GB	24–35 Mbps	405 nm, $NA = 0.85$
Video editing (Digital Video, DV)	28 Mbps	22 GB	30–50 Mbps	405 nm, $NA = 0.85$
2 streams of HD video	2–24 Mbps	40 GB	80 Mbps	405 nm, $NA = 0.85$

of 9 GB (for 2 h of each steam) or more.
3) Recording of 2 h of HDTV video (*e.g.* according to the Japanese BS4B standard at 24 Mbps) requires a 22 GB disc capacity and a data rate of 35 Mbps.
4) Editing of digital video camcorder recording (*e.g.* DV at 28 Mbps raw data rate) requires a 30–50 Mbps data rate (depending on the editing options) combined with fast random access.

These application areas are summarized in Table I, together with the key parameters (required disc capacity and data rate) and the system options for realizing them. The application, capacity and data rate requirements imply that the disc format needs to be highly efficient and should support fast access. Additionally, the optical disc system needs to be highly robust and reliable.

Therefore, for full featured digital home video recording without the loss of picture quality, rewritable optical discs with capacities of 9 GB and data rates of 33 Mbps are required at least. In the near-future, 22 GB and 50 Mbps will be required for a video recorder with sufficient recording time for HDTV recording and new user features.

3. Disc Structure

A rigid 1.1-mm-thick poly-carbonate substrate is covered with a phase-change stack, deposited in reversed order compared to the standard CD-RW or DVD+RW phase-change stacks (Fig. 1). On top of this stack a 0.1-mm-thick cover layer is applied by spin coating or foil lamination.[5] This thickness of 0.1 mm allows for sufficient tilt margin at $NA = 0.85$: when using a blue-violet laser, the tilt margin is approximately equal to that of DVD (650 nm, $NA = 0.60$, 0.6 mm substrate). The cover layer can be made with a thickness variation well within $\pm 3\,\mu$m. With this thickness uniformity, there is no need for dynamical spherical-aberration correction, so a rigid dual-lens objective can be used. The substrate serves as a stiff and rigid carrier, containing the mastered information (embossed data and grooves). We use standard astigmatic or Foucault wedge focussing methods and the radial push-pull method for tracking.

4. Error Detection and Correction

Compared to DVD ($NA = 0.60$, 0.6 mm substrate thickness), the $NA = 0.85$, 0.1 mm cover layer disc system has one drawback: the spot size on the entrance surface of the disc is reduced from approximately 0.50 mm diameter (0.20 mm^2) to 0.14 mm diameter (0.015 mm^2). This results in increased sensitivity to dust and scratches on the disc surface, which may

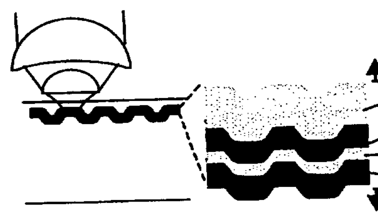


Fig. 1. Disc structure.

cause burst errors, on top of the usual random errors during readout of the recording layer. Our so-called picket code is a new error detection and correction method that uses two correction mechanisms to handle these errors effectively: a long-distance code (LDC) combined with a burst indicator subcode (BIS).

4.1 Long-distance code (LDC)

The LDC has 304 [248, 216, 33] Reed-Solomon (RS) code words. Each 9.5 RS code word contains the user data bytes of one logical 2 K information block (with 4 additional bytes used for extra error detection). The LDC has sufficient parity symbols and interleaving length for correcting random errors, multiple long bursts and short bursts of errors. The burst error correction capability is strongly enhanced by using erasure correction on the erroneous symbols flagged by the BIS code described below.

4.2 Burst indicator subcode (BIS)

The LDC is multiplexed with the synchronisation patterns and the BIS. The BIS has 24 [62, 30, 33] RS code words (Fig. 2). The latter carries address and control information strongly protected by these BIS-RS code words. In fact, the BIS code can be properly decoded (i.e. all its errors can be corrected) with extremely high probability. The location of its corrected bytes and erroneous synchronization patterns serve as "pickets" indicating the likely position of long burst errors in the LDC data between these pickets: when subsequent pickets have "fallen", it is highly likely that all the data located physically in between these pickets was also detected erroneously. The LDC can use this information to perform erasure correction (see above).

4.3 Data organization and data access

The protection is over physical clusters of 64 K user data, which are organized in 16 physical 4 K blocks. Each 4 K

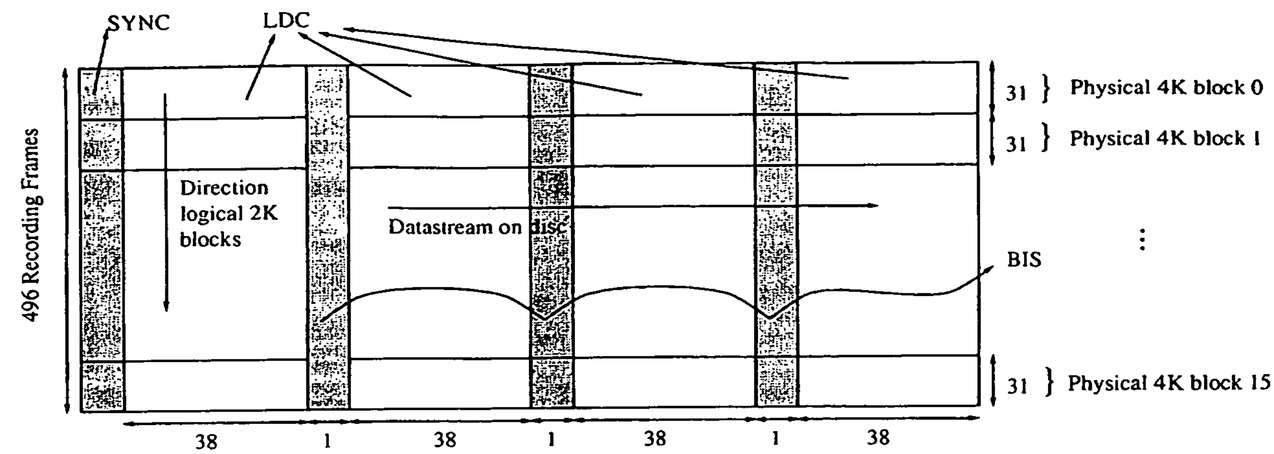


Fig. 2. ECC structure of 64 K physical cluster with LDC and BIS columns.

Table II. Parameters and comparison of the ECC schemes of DVD (product code) and DVR (LDC + BIS Picket code).

Parameters	DVD	DVR
ECC rate (fraction user data bytes/ECC bytes)	0.866	0.852
Cluster size	32 kB	64 kB
Logical sector size and data	2064 bytes: — 2048 user data; — 4 EDC bytes; — 12 bytes for address, copyright management, spare	2074.5 bytes: — 2048 user data in LDC; — 4 EDC bytes in LDC; — 22.5 bytes in BIS for address, copyright management, spare
Code construction	product code	long distance code + burst indicator (Picket)
Code parameters	RS[182, 172, 11] × RS[208, 192, 17]	304 × RS[248, 216, 33] + 24 × RS[62, 30, 33]
Maximum correctable burst length (MCBL)	2912 ECC bytes	9920 ECC bytes (17.3 mm)
Number of correctable bursts of 100 ECC bytes	8–29	32–99 bursts of 175 μm
Number of correctable bursts of 200 ECC bytes	5–14	32–49 bursts of 349 μm
Number of correctable bursts of 300 ECC bytes	5–9	16–33 bursts of 524 μm
Number of correctable bursts of 600 ECC bytes	3–4	10–16 bursts of 1047 μm

block is again subdivided into 31 recording frames (see §6.3). To obtain the user data of one logical 2 K block we only need to decode the BIS having all address information together with the corresponding 10 RS code words in the LDC. This gives quick access to logical 2 K blocks since the 64 K LDC code does not have to be fully decoded.

4.4 *Parameters of the picket LDC + BIS code and comparison with a conventional product code*

In DVD, a product code is used for error correction.[10] The horizontal code is intended for correcting random errors and for indicating the location of burst errors. The vertical code uses erasure decoding to correct these bursts. The picket code does not have a horizontal code, all the redundancy is put in the vertically oriented LDC and BIS codes.

In the picket code, the BIS and the synchronisation patterns are used for indicating the location of bursts (see §4.2). An errors-and-erasures decoder of the LDC corrects these bursts together with random errors. Thus, compared to the vertical code in a product code, the picket code has approximately twice as many parity bytes in its vertically oriented composite codes.

In Table II we compare the ECC schemes of DVD and DVR. In DVD the cluster size is 32 kB, while we use a cluster size of 64 kB for our code, which again leads to a doubling of the number of parity bytes. We use this extra redundancy, together with the redundancy provided by the picket construction (described above), for increasing the interleaving length as well as the minimum distance of the vertical code. This improves the burst error capacity with a factor of 3 to 4. This is demonstrated in Table II, where burst errors of various lengths are considered. For example, when no random errors are present, between 16 and 33 bursts of 300 ECC bytes (corresponding to 524 μm along a track) can be corrected in DVR, whereas the DVD-ECC can only correct between 5 and 9 bursts of 300 ECC bytes. Also the maximum correctable burst length (MCBL) in DVR is more than three times the MCBL in DVD: 9920 vs 2912 ECC bytes. Both codes have comparable ECC rates (the difference is mainly in available space for address, control, copyright management and spare area), and both codes are able to adequately correct the amount of random errors for their applications.

4.5 *Performance analysis using experimental data*

The performance of our code is illustrated by the following example, taken from our analysis presented in detail in ref. 11. On a dust sprayed disc exposed to an office environment, we find a raw byte error rate of 4×10^{-3}. The errors include many long and short burst errors. After analysis of the error patterns on this disc, a model can be made allowing us to study the error rate dependence on error classes and, *e.g.*, error density, thus generalizing the specific measurements on this disc and allowing us to determine the error rate after error correction. It is then found that our BIS code retrieves the address information and burst indication very reliably: the error rate is below 10^{-25}. The LDC-code powerfully corrects the raw byte error rate to 1.5×10^{-18} using erasure correction of the erasures flagged by the BIS-code. This has to be compared with an error rate of 5.7×10^{-7} which would have resulted after error correction with the DVD ECC.

Since the error rate after correction is very low, it is not experimentally feasible to measure the error rate after error correction when using this powerful ECC on real discs. We here demonstrate the power of the use of the BIS data as pickets for erasure flagging by comparing the number of parities used in the LDC to correct all errors. On a standard disc, we added 2–4 bursts in the information layer of 300 μm length (2250 channel bits) each per ECC block. When just using the LDC, 17% of the error correction capacity was required to correct all errors. With the use of the BIS data, 72% of all errors was flagged as an erasure, all corresponding to the burst errors that were added by us, and the required correction capacity was reduced to 11%. If all burst errors were completely flagged as erasures, this could have been reduced to 8.5% (half of 17%). The difference is explained largely on the basis of the parts of the bursts before and after, respectively the first and last BIS byte related to the burst: only when all bursts start and stop exactly at a BIS position, the reduction of the number of required parity symbols by the exact factor of two is achieved. This example shows that the use of BIS for erasure flagging can result in a significant reduction in the required error correction capacity.

5. Channel Modulation

The channel modulation schemes for CD-ROM and DVD-ROM were optimized for the maximum efficiency (i.e. high user capacity) within the constraints given by the modulation transfer function, i.e., the optical resolution limit. For rewritable phase-change recording however, a noise factor is introduced: when overwriting old data, differences in optical absorption and thermal properties between the old amorphous and crystalline areas result in a distortion of the newly written data. This yields variations on the effective mark position, showing up as additional jitter. We have designed our channel modulation scheme in such a way that the peculiarities of rewritable phase-change media are taken into account.

We developed a new ($d = 1, k = 7$) RLL code. The (1, 7) constraint means that we use runlengths of 2T up to 8T, with T being the channel period. The rate of this code is 2/3 (DVD's 8/16 modulation, also called EFMplus,[12] is a (2, 10) RLL code with a rate of 1/2). Using our code, the channel bit length is increased at the same data bit length compared to 8/16 modulation. This gives a larger timing tolerance, hence lower jitter (see Fig. 3) and longer recording time. Our code is named after its two new characteristic additional features: (1, 7) RLL Parity-Preserve, Prohibit Repeated Minimum Transition Runlength code, abbreviated as 17PP. We describe these features below.

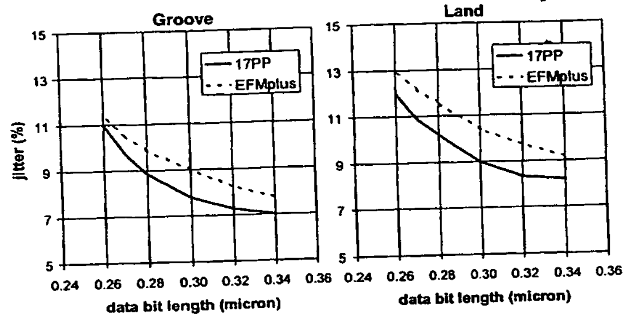


Fig. 3. Jitter comparison vs density for 17PP ($d = 1, k = 7$, rate 2/3) vs EFMplus (8/16 modulation; $d = 2, k = 10$, rate 1/2). The data is measured at $\lambda = 640$ nm, $NA = 0.60$, on a Land/Groove substrate (DVD conditions) after 10 times overwriting: a) in groove, b) on land.

5.1 *Parity preserve*

Our code has the parity-preserve property,[13] which means that the number of '1'-s in the data bit pattern before the channel encoder and in the corresponding modulated bit pattern after the channel encoder are both even, or both odd. For example, in our code the odd-parity data bit pattern '01' modulates into '010' and '10' into '001', and the even-parity '11' into '101' (or '000'). Using this property, one can efficiently obtain, and guarantee, a low DC-content of the recorded signal, thus allowing high-pass filtering of the playback signal, which makes the bit detection largely insensitive to signal level variations by *e.g.* dust and scratches, thus giving a highly reliable playback. The DC control is performed using insertion of DC-control bits in the data bit stream before the channel encoder, in contrast to alternative merging bit schemes where the so-called merging bits are inserted in the channel bit stream. We thus reduce the overhead for DC-control from 5.8% in conventional (1, 7) RLL with merging bits to 2.2% in our 17PP code, at the same DC-control block length.

This new DC-control mechanism is illustrated using the following example. Consider the data bit pattern 'P1 10 01 10 01' to be encoded with the modulation table, where P denotes a DC control bit. When 'P' = '1', this data bit pattern would encode into '101 001 010 001 010', which translates in a bit pattern '001 110 011 110 011' after NRZI conversion: this has a digital sum value (DSV) of +3. With 'P' = '0', it encodes into '010 001 010 001 010', which translates in '100 001 100 001 100' after NRZI conversion and has a DSV of −5. Thus we can choose between a positive and a negative digital sum value for the resulting bit sequence, and by the proper choice we can keep the low frequency content of the resulting modulation bit stream small.

A comparison of the power spectral densities between our code (using one DC control bit for every 45 data bits) and a conventional (1, 7) RLL code with merging bits for DC-control at the same overhead is shown in Fig. 4.

5.2 *Prohibit RMTR*

Our code limits the number of consecutive minimum runlengths (i.e. runs of 2T) to 6: the prohibit RMTR (repeated

minimum transition runlength) property. This increases system tolerances, especially against tangential tilt as shown in Fig. 5, and hence increases the robustness of the system.

The RMTR is implemented in the modulation scheme by a careful choice of the code words and by using a substitution rule that prevents the appearance of a long sequence of the minimum runlengths. The data bit pattern '01 *11 01 11* 01' would be modulated into the channel bits '010 *101 010 101* 010', i.e. '100 *110 011 001* 100' after NRZI conversion, when the main conversion table is used. This repetition of 2T symbols is prevented by a substitution of the bits printed in italics resulting into '010 *001 000 000* 010', i.e. '100 *001 111 111* 100' after conversion to NRZI.

6. Address Format

The rigid carrier substrate contains the land/groove spiral and embossed headers. The groove forms a single spiral with a pitch of 0.90 μm, with the lands in between, resulting in an effective track pitch (land-to-groove) of 0.45 μm. Each track (one turn of the spiral) is divided into eight segments, shown in Fig. 6(a). Each segment starts with an embossed header area, and is followed by a wobbled groove.

6.1 Wobble scheme

The wobble is used for speed control of the disc and to derive the channel clock during recording (the channel bit length of the data is an integer fraction, 1/322, of the wobble period).

In designing a wobble scheme, two conflicting properties have to be considered in the design of the format to obtain the maximum format efficiency. On one hand, a constant linear density format allows maximum efficiency, since that gives no losses due to density variations. This implies the use of a wobble with a constant spatial frequency, i.e. a so-called CLV (constant linear velocity) wobble. On the other hand, the use of a CLV wobble cannot be applied in a land/groove system, since that would result in a wobble signal with variable amplitude on the land tracks because the wobbles in the grooves on either side have a slightly different angular frequency ('wobble beat').

Therefore, we have chosen to use a zoned CAV (constant angular velocity) wobble: the zoning of the rewritable user area is done into 99 bands of 762 tracks each (i.e. 381 groove and land tracks). Within a band, the number of wobbles per segment is constant, thus providing a single-angular-frequency wobble in both groove and land tracks. The number of wobbles per segment increases from 420 in the first track by a fixed number (6) in every next band, in such a way that the spatial wobble frequency at the start of each band is exactly the same. The wobble period is thus constant over the whole disc within ±0.8%, resulting in a practically constant

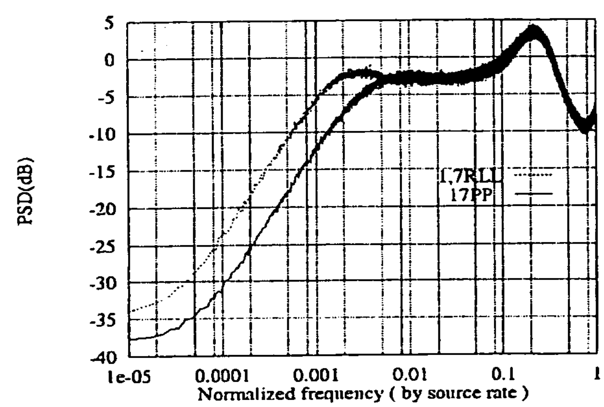


Fig. 4. Power spectral density (PSD) comparison at the same DC overhead between 17PP (1 source bit every 46 source bits) and (1, 7) RLL with merging bits (4 channel bits every 184 channel bits).

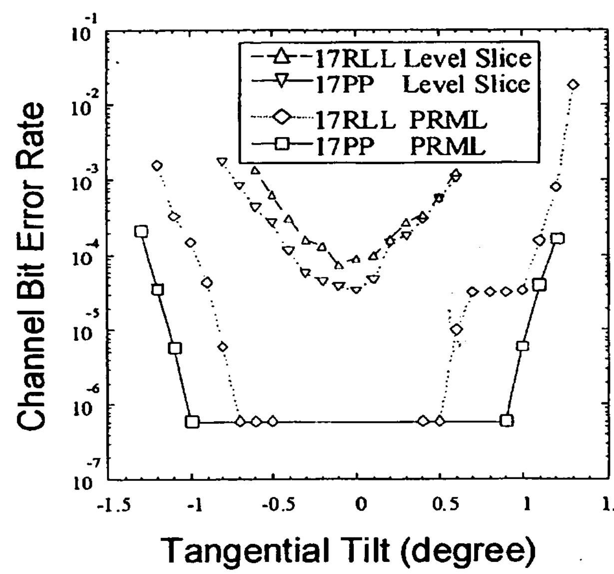


Fig. 5. Effect of the use of P-RMTR: Channel bit error rate vs tangential tilt (at a 10% increased linear density to 0.19 μm/data bit, after 1000 times of overwriting) using standard slicing level detection and when using PRML detection.

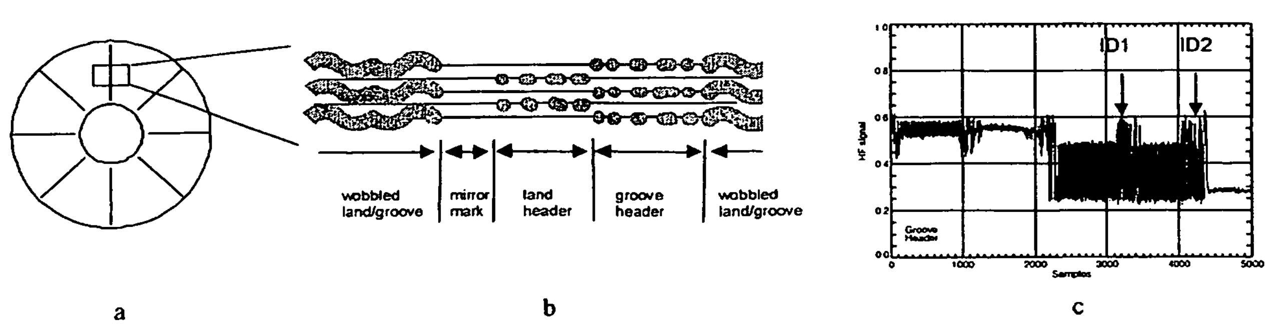


Fig. 6. Address format: a) header layout, b) header structure showing mirror mark, land header, groove header, and wobbled land/groove structure, and c) signal from groove header showing the two address fields (ID1 and ID2) and two spatially separated positions.

linear density.

The number of wobbles added every band (6 per segment) and the size of the bands (762 tracks) are chosen for achieving the maximum efficiency. This choice is the balance point when taking into account the two sources of efficiency loss: 1) the wobble period variation, which becomes larger when the bands become larger; and 2) the loss of one track at each band boundary, i.e. the land track suffering from wobble beat due to different wobble frequencies on either side, which gives a larger efficiency loss when bands become smaller.

6.2 *Header*

The header has three parts: a mirror mark, a land header and a groove header (Fig. 6(b)). The mirror mark can be used as a calibration or reference field (offset control) for push-pull tracking and focus. The header itself contains the track and segment numbers for addressing in the so-called identifier field (ID). In each header, this ID is repeated a second time at a physically separated position to be well protected against small dropouts, *e.g.* defects in the layer stack (Fig. 6(c)). Groove and land headers are separated in the tangential direction to prevent cross-talk between the two. The robustness of the headers is further increased by using a $d = 2$ modulation code with the same channel bit length as the 17PP-encoded phase-change data, resulting in a large signal amplitude also for the shortest marks (I3) and a very wide eye opening (Fig. 7). This results in data-to-clock jitters below 6% in the header, and we measured an address error rate below 10^{-4}, illustrated in Fig. 8.

6.3 *Organization of data on the disc*

In most optical disc systems, the physical structure of the user data and the physical structure of the address format (esp. headers) are, what one could call, synchronized. Typically, the distance between two headers is then equal to the (fixed) recording unit fragment size of, *e.g.*, 2 kbytes. In our scheme, this is no longer the case: the distance between the headers increases every band with 6 wobble periods and thus varies from the inner diameter of the disc (where the distance is 420 wobbles, see §6.1) to the outer diameter by a factor of roughly 2.5. For maximum efficiency, the data is organized in so-called recording frames with the length of 6 wobbles, or 1932 channel bits (a SYNC, 4 times 38 LDC bytes and 3 BIS bytes, see Fig. 2), such that an integer number of these frames fits exactly in between two headers. These frames are the basic units of our recording scheme. When recording a 64k ECC cluster, equivalent to 496 frames, recording is stopped just before a header, and resumed again after the header, as shown schematically in Fig. 9. The next ECC block is written subsequently: linking between the blocks is thus not always done at a header position, but can also be done in between two headers. Of course, the start positions of all ECC blocks are known, and can be referred to by the combination of track number, segment number and wobble number.

6.4 *Efficiency*

The combination of a fixed number of headers per revolution in a spoke-like layout, our efficient wobble-scheme with practically constant linear density and our recording scheme results in a very high efficiency for our land/groove address format: 96.6%, compared with 88% for DVD-RAM's land/groove format (which has a larger density variation over the disc and more overhead from headers).[14] This results in a large capacity (long recording time) and highly reliable recording and playback. Moreover, the structure supports fast access.

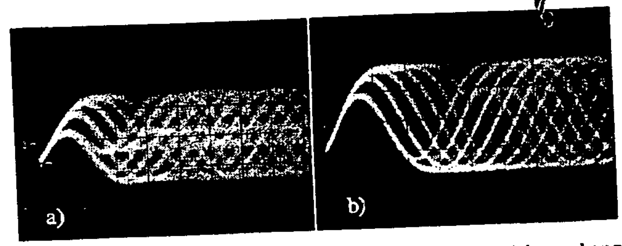
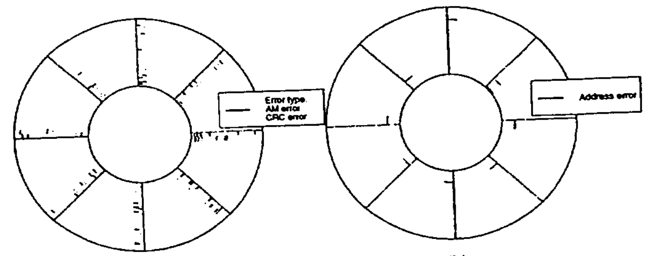


Fig. 7. Non-equalized eye patterns for a) 17PP code for (phase-change) data and b) (2, 7) RLL code for embossed header data.



(a) (b)

Fig. 8. Graphical presentation of header errors and the various sources of errors: an Address error occurs when none of the two address fields in a header is detected correctly. A misdetection can occur due to two reasons: the synchronization patterns of an address field, the so-called Address Marks (AM), can be missed, or the parity check symbols (CRC) can flag a detection error. Both errors are indicated for each address field of all groove headers.

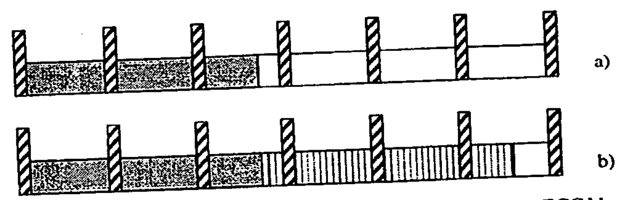


Fig. 9. Schematic representation of recording scheme: a) a first ECC block (filled gray) is written with interruptions at the header positions (diagonally hatched); b) the second ECC block is written subsequently (vertically hatched).

7. System Integration and Evaluation

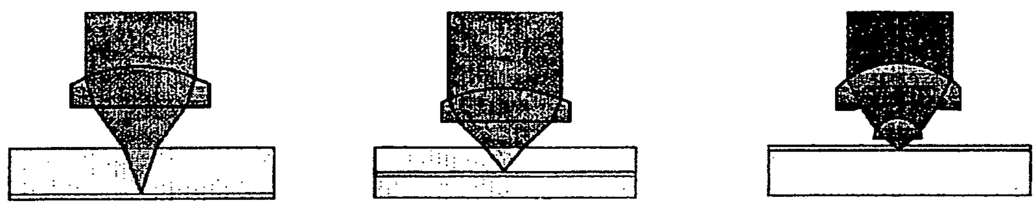
We have implemented our format on thin-cover layer[5] phase-change discs[6,7] and in an experimental optical disc drive equipped with a two-element $NA = 0.85$ objective[1–3] and a red laser. The parameters are summarized in Table III.

The headers are detected highly reliably using standard slicer level detection: the data-to-clock jitter is below 6% and the header error rate is below 10^{-4} (see §6.3). The wobble is robustly detected using the high-frequent radial push-pull signal, thus providing a stable write clock that is locked to the disc. Phase-change recording using our 17PP code at a data bit length of 0.210 μm and 9.2 GB disc capacity was performed with low data-to-clock jitter, less than 9%, at data rates of 33 Mbps, also after many overwrite cycles. We have

Table III. DVR parameters.

Disc diameter	120 mm	Disc layout	Wobbled groove and land with headers
Cover layer thickness	$100 \pm 3\,\mu m$		
Effective track pitch	$0.45\,\mu m$	Data zone division	99 ZCAV bands
Channel bit length	$0.14\,\mu m$	Channel modulation	Phase-change: 17PP
Data bit length	$0.21\,\mu m$		Headers: (2, 7) RLL
Total efficiency	79%	Error correction code	64 kB LDC + BIS Picket
User data capacity	9.2 Gbyte	Laser wavelength	650 nm
Channel bit rate (typ.)	62.5 Mbit/s	Numerical aperture	0.85
User data rate (typ.)	33 Mbit/s	Objective type	(rigid) dual-lens

Table IV. Optical recording generations: CD, DVD and DVR systems.

generation	first	second	third	
	CD	DVD	DVR	
				
wavelength	780 nm	650 nm	650 nm	400 nm
NA	0.45/0.50	0.60	0.85	0.85
substrate thickness	1.2 mm	0.6 mm	0.1 mm	0.1 mm
capacity (single layer)	650 MB	4.7 GB	9.2 GB	22 GB
data rate (1X)	1.2 Mbps	11 Mbps	33 Mbps	35–50 Mbps
introduced as	CD-Audio distribution	DVD-Video distribution	Digital Video recording	Digital Video recording

recorded large streams of MPEG video data, encoded with our ECC and channel code. This data was read-back without any errors: the ECC corrected all random errors as well as the occasional burst errors (see §4.5), resulting in error-free user data (LDC) and access data (BIS).

We are currently extending and implementing the format in an experimental drive using blue-violet diode lasers (λ around 405 nm). The initial results show that a 22 GB capacity and 30–50 Mbps user data rate are feasible with our approach.

This shows that our DVR system is suitable for next-generation optical disc systems, after CD and DVD (Tabel IV). Moreover, we believe the main application area for such a system will be in-home consumer recording of digital video streams of both standard as well as high definition quality.

8. Conclusions

We have presented a complete, novel format (error correction code, channel modulation code and address format) for a digital video recording system with a disc capacity of 9.2 GB and a user data rate of 33 Mbps with the use of phase-change recording with a red laser and $NA = 0.85$ through a thin cover layer. The format is designed for optimum performance for real-time digital video recording: the address format, recording scheme and error correction scheme allow fast random access, as well as fragmented recording (*e.g.* for efficient use of the empty space on a partially written disc), and the efficient format combined with our 17PP channel code results in a high disc capacity (9.2 GB). This allows recording of 4 h of DVD quality video. When used in combination with our fast phase-change stacks (over 33 Mbps user data rate), it also allows dual-channel operation, *e.g.* writing one video programme while reading another one at MPEG2 bit rates of, say, 10 Mbps. In addition, transparent recording of HDTV formats is possible.

The DVR optical disc system parameters are summarized in Table III. The total efficiency of address format, DC-control and error correction is 79%, which is very high for a random access optical recording system. Most of the overhead is used to guarantee system robustness: a powerful and effective error correction, efficient and guaranteed DC-control, robust addressing by efficiently designed headers, and robust and reliable phase-change recording behaviour.

This format allows extension to even higher capacities. With blue-violet lasers (λ around 405 nm), we will be able to obtain a capacity of 22 GB and more, which is necessary for 2 h of high definition TV recording.

Our system is well suited to be the basis of a third-generation optical recording system.

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